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IMPROVEMENT OF SOLID FILM LUBRICANTS  
AND UNLUBRICATED BEARING OPERATION

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RESEARCH AND TECHNOLOGY DIVISION  
AIR FORCE SYSTEMS COMMAND  
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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## FOREWORD

This report was prepared by the Fluid and Lubricant Materials Branch, Nonmetallic Materials Division, Air Force Materials Laboratory, Research and Technology Division, with Mr. B. D. McConnell acting as project engineer. The preparation of the report was initiated under Project 7343, "Aerospace Lubricants", Task 734302, "Dry and Solid Film Lubricant Materials".

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This Technical Memorandum has been reviewed and is approved.

  
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## ABSTRACT

Results are presented for the performance of unlubricated ball bearings operating at 1750 rpm in a vacuum of  $10^{-7}$  Torr or less. One precision bearing is still operating after 7000 hours under these conditions. The wear life improvement of solid film lubricant by means of various techniques is discussed. These techniques include double deposition, plasma spraying, metal coating of lubricant powders, and compacting. Improvements of as much as a 50 fold increase have been achieved.

# UNLUBRICATED BEARING OPERATION

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Anderson and Glenn have discussed several interesting factors in covering the effect of space environment on both lubricants and rolling element bearings. They have stated the importance of bearing design in the successful operation in a space or vacuum environment. They have also discussed how successful lubrication in vacuum may not depend upon the bulk properties of lubricants but on the existence of a thin, tenacious monolayer of lubricant which apparently does not evaporate and is very hard to remove. We agree with the authors that bearing design is much more critical for space operation and would like to discuss some tentative test results which we feel verify these observations.

## TEST DEVICE

These tests have utilized several small vacuum bearing rigs which were designed to be as simple as possible to allow investigation of the effect of long term exposure to vacuum on the performance of dry lubricated bearings (Reference 1). A schematic of the bearing rig is shown in Figure 1. The test chamber is ion pumped to insure no pump oil contamination. The test bearing is a size 204 (22 mm bore) and is rotated at 1,750 rpm by means of a magnetic coupling. The weight of the rotating shaft and magnet plus the attraction of the magnets places an

axial load of approximately seven (7) pounds on the bearing. An eight (8) liter per second ion pump maintains a pressure of  $4 \times 10^{-7}$  Torr or less while the bearing is rotated. The test procedure includes mounting the bearing into the test chamber and pumping to the desired pressure. The motor and driving magnet are then raised so that the magnetic coupling between the two magnets is established through the bottom of the test chamber. The motor speed is slowly brought up to full speed by means of a rheostat. The running friction or torque of the bearing is measured by coast-down time. A coil wrapped around the lower end of the test chamber senses an induced voltage due to the rotation of the inner magnet. The driving motor is quickly lowered and the time for decay of voltage and rotation is measured. Coast-down time is normally checked about 2 times daily. Frictional torque has been calculated and plotted as a function of coast-down time (Reference 2).

#### INFLUENCE OF BEARING DESIGN

We have some preliminary data from a program with these rigs which we feel support the idea that bearing design, especially the ball separator or retainer, exercises a great influence on bearing performance. In this program five ball bearings which had different retainer designs were selected and were tested in a vacuum environment without lubrication (Reference 3). These bearings are listed in Table 1 as to type, manufacturer, material, and type of retainer.

The bearings were initially cleaned in an ultrasonic bath with stoddard solvent for 40 minutes followed by a 60 minutes soak in clean acetone to remove the residual preservative oil in which the bearings were packed. In all cases this oil is believed to be MIL-L-6085A, a

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di-ester based fluid. After cleaning and air drying, the bearings were carefully placed into the test chambers taking care not to contaminate them. The test chambers were evacuated with a mechanical roughing pump and then ion-pumped down to a low pressure ( $1 \times 10^{-7}$  Torr) before rotation was started. After speed and pressure were stabilized, the test rigs were allowed to run continuously and unattended except for periodic checks of pressure and coast-down time. The test results are shown in Table 2.

The first tests were conducted with bearing A, a precision bearing previously used in ultra high speed bearing studies ( $> 30,000$  rpm). One bearing is still running with over 7,000 hours of operation. The bearing friction torque has remained between 0.05 and 0.09 oz-in. Chamber pressure has been maintained at  $1 \times 10^{-7}$  Torr or less. The duplicate bearing in this test was stopped after 1604 hours of operation to try to determine why these bearings, unlubricated, were still running so smoothly after this length of time in a high vacuum environment.

There were no signs of wear on either the inner or outer race or the balls of this bearing. The bronze retainer had been worn slightly where the outer race was contacted. Some wear in the retainer ball pockets was also noted. The wear debris was in the form of a fine, bronze-like powder, some of which appeared to be burnished or rolled onto the race surface until it became so thin it appeared transparent under microscopic examination. This was not felt to be the lubricating mechanism and the bearing was subjected to further study and analyses.

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The entire bearing was cleaned by boiling in ether to obtain a concentrate for infrared analysis to determine if any of the preservative oil or roughing pump oil might be present. The analysis of this concentrate was compared to the analyses of a sample of the roughing pump oil and the preservative oil taken from the foil wrappers of the bearings. The comparison showed traces of the preservative oil in enough quantity to be able to definitely identify it.

The second tests were conducted with bearing B which has a stamped, ribbon, ball-riding separator. Three of these bearings ran for an average of 3.57 hours with over 3 oz-in of torque. The bearings failed to start after coast-down time checks; the bearing torque exceeded the magnetic coupling break away torque (44 oz-in).

The third tests were conducted with bearing C, which had the Niresist retainer. These bearings were selected for comparison with similar data reported by other workers (References 1 and 2). Their data indicated that a lifetime of about 2 minutes could be realized for these bearings running under these conditions. For these tests, operating times of 1.3 and 1.0 hrs were obtained, with the operating speed of the 1.0 hour run limited to 450 rpm. The difference in operating time between these tests and the earlier data (1.3 hours versus 2 minutes) cannot be readily explained. However, it was found that the cleaning procedures were quite different. Their procedure included rinsing in acetone, vapor-degreasing in trichlorethylene, and then polishing with levigated alumina.

The fourth tests were conducted with bearing D, similar to bearing C except that the separator is made from machined steel. The average

wear life of these four experiments was 47.4 hours using the cleaning procedure first mentioned (ultra-sonic in stoddard solvent followed by acetone soaking). These tests, and those of the fifth series, show an influence of separator material upon the performance of the bearing.

The fifth tests were conducted with bearing E, which has a silver-plated ribbon separator. These bearings are similar in physical configuration to bearing B. The average wear life for the three experiments with E bearings was 378.3 hours, again showing the influence of separator material upon bearing life.

There are felt to be several factors which could influence the performance exhibited by these bearings. We do not wish to completely discount the presence and effect of residual lubricant from the preservative oils. But we feel that the fact that the cleaning technique was the same for all bearings, and yet orders of magnitude difference in life are observed, that retainer design is a major influence. The design of the different retainers allows greater ball-retainer contact area with the ribbon and heavy machined retainers than with the thin cylindrical retainer of the precision bearing. The amount of contact area between the ball and retainer influences the wear rate and possibly the wear debris particle size. Retainer material may also play an important role as shown by the differences in the results between bearings B and E and bearings C and D. Bearing precision is certainly important since the more precise bearings tend to have better balanced retainers.

## CONCLUSIONS

These limited data cannot be conclusive but we feel they tend to establish the trend that design and materials can greatly influence the performance of a bearing operation supposedly unlubricated in a high vacuum environment.

TABLE 1

Bearing	Manufacturer	Bearing No.	Ball & Race Material	Retainer Type	Retainer Material	ABEC # or Grade
A	Barden	S204HX100K6	52100	Thin cylinder outer land riding	Bronze	7
B	Jack & Heintz	AF3110-144-8510	52100	Ribbon	Pressed Steel	1
C	MRC	204R-16	52100	Thick cylinder outer land riding	Cast Niresist	5
D	New Departure	14047D	52100	Thick cylinder outer land riding	Machined Steel	Class II
E	MRC	204S17	52100	Ribbon	Silver Plated Pressed Steel	3

TABLE 2

## VACUUM BEARING TESTS - PRELIMINARY RESULTS

Bearing	Test No.	Pressure (torr)	Bearing Torque (oz-in)	Operation Time (hrs)
A	1	$8 \times 10^{-9}$ to $2 \times 10^{-7}$	0.05-0.09	7,000 (no failure)
	1	$5 \times 10^{-9}$ to $5.2 \times 10^{-8}$	0.08-0.13	1604 (test terminated) (no failure)
B	2	$7.5 \times 10^{-7}$	>3	4
	2	$9.7 \times 10^{-7}$	>3	6.7
	2	$2 \times 10^{-7}$	>3	3 min
C	3	$7.3 \times 10^{-8}$	>3	1.3
	3	$1 \times 10^{-6}$	>3	1.0
D	4	$5 \times 10^{-8}$	0.9	24.5
	4	$9.8 \times 10^{-8}$	0.3-0.9	110.8
	4	$7 \times 10^{-7}$	0.5->3	8.2
	4	$9.2 \times 10^{-7}$	>3	45.9
E	5	$8.4 \times 10^{-8}$	0.3-0.9	529.5
	5	$7.8 \times 10^{-8}$	0.25-1.5	327.5
	5	$7 \times 10^{-8}$	0.3-2.0	277.9

## IMPROVEMENT OF SOLID FILM LUBRICANTS

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Mr. Devine has discussed how the correct combination of lubricant materials, bearings, and design criteria is essential for long term operation of mechanical systems utilizing solid lubricants. A great deal of research has been devoted to the search for new materials or formulations which will hopefully exhibit long periods of operation while maintaining low friction and wear. Other studies have shown the importance of processing or application of these type materials in obtaining very long wear lives.

These studies have stressed development of new methods or techniques for applying solid film formulations rather than variations in the normal spraying or dipping methods. Also, these techniques are used with existing, well known solid film lubricants and do not place emphasis on development of new materials or formulations. These techniques include vacuum deposition, plasma spraying, and electrophoresis which have been used successfully to apply various solid film lubricants. Also, combinations of some of these techniques have proven useful in increasing the wear life performance of solid lubricants. For instance, the Air Force Materials Laboratory has demonstrated the potential for increasing the wear life of ceramic bonded solid film lubricants many fold through the technique of densifying the film. This technique, termed "double deposition", consists of the application of a second coating of lubricating material by electrophoresis into the porous

structure of the first sprayed and cured coating. The wear life of a MoS<sub>2</sub>-PbS film bonded with a ceramic-metallic oxide binder was increased over fifty (50) fold with the application of a MoS<sub>2</sub>-B<sub>2</sub>O<sub>3</sub> formulation by electrophoretic deposition (Reference 4). The increase in wear life was found to be due to the dense, uniform, well-bonded film and not increased film thickness. The MoS<sub>2</sub>-PbS film as normally sprayed and cured, exhibited a wear life of about 14,000 load cycles when tested at 600 rpm, 25 pound load, 600°F, and  $1 \times 10^{-6}$  torr in a dual rub shoe tester. The wear life of the densified film was over 900,000 load cycles when tested under the same conditions. Figure 2 compares these results and also shows the effect of temperature on the wear life of this film.

#### Plasma Spraying of Solid Lubricants

Other methods of application and processing of solid lubricating materials are currently being investigated. Equipment and techniques have been developed which permit spraying solid lubricants such as MoS<sub>2</sub> through a plasma torch without excessive degradation (Reference 5). Self-lubricating materials such as PTFE have also been successfully applied to substrate metals with these techniques. The plasma spraying technique also allows the application of high temperature ceramic bonded formulations to lower temperature substrate materials without excessive heating of the substrate. The ceramic binder is heated sufficiently into the plasma stream to melt and bond the lubricating materials without subsequent curing. Development of a dual injection port plasma gun allows the binder to be injected into the hot zone while the lubricating material is injected downstream in a cooler portion of

the plasma stream. This permits application of many solid lubricant formulations which would otherwise be seriously degraded in the hot plasma stream.

The plasma spraying process has great potential for application of solid lubricants in the field where no curing facilities are available. The process also lends itself to rapid coating of parts in high speed production lines.

#### Metal Coated Lubricant Powders

The investigation of the plasma spraying process led to the development of some new, potential lubricating materials. In an effort to find new ways to protect the lubricant particles while they were traveling through the plasma stream, a method for coating the particles with a thin metal shell was found. A fluidized-bed reduction process was utilized to coat  $\text{MoS}_2$  and graphite powders with thin coatings of silver, copper, or nickel (Reference 6). Thermogravimetric studies with Ag-coated  $\text{MoS}_2$  in air indicated a marked improvement in thermal stability compared to uncoated  $\text{MoS}_2$  (Figure 3).

The type materials can be applied with a standard plasma gun without serious degradation of the lubricant powders. The films obtained with these coated materials can be used at higher temperatures due to the protection offered by the metal coating.

#### Solid Lubricant Compacts

The use of powder metallurgy techniques has been utilized in the processing of solid lubricating materials. The normal powder forms of lubricants such as graphite and  $\text{MoS}_2$  together with metal powders have been pressed under high temperatures and pressures to form solid bodies.

These solid bodies, called compacts, have very high compressive strength and can be machined and otherwise handled as metal parts.

These type materials, such as a  $\text{MoS}_2$ -Ta-Fe combination, have shown great potential as separators for high speed ball bearings and as low speed plain journal bearings, for both air and vacuum operation (Reference 6). Feasibility of extended ball bearing operation with only transfer film lubrication from these lubricant compact materials in a ball separator design has been demonstrated. Figure 4 shows a separator. Tests have been conducted with 204 size bearings with a 10 pound axial load and 3450 rpm. Over 6,500 hours of continuous operation was obtained with very low pocket and ball wear.

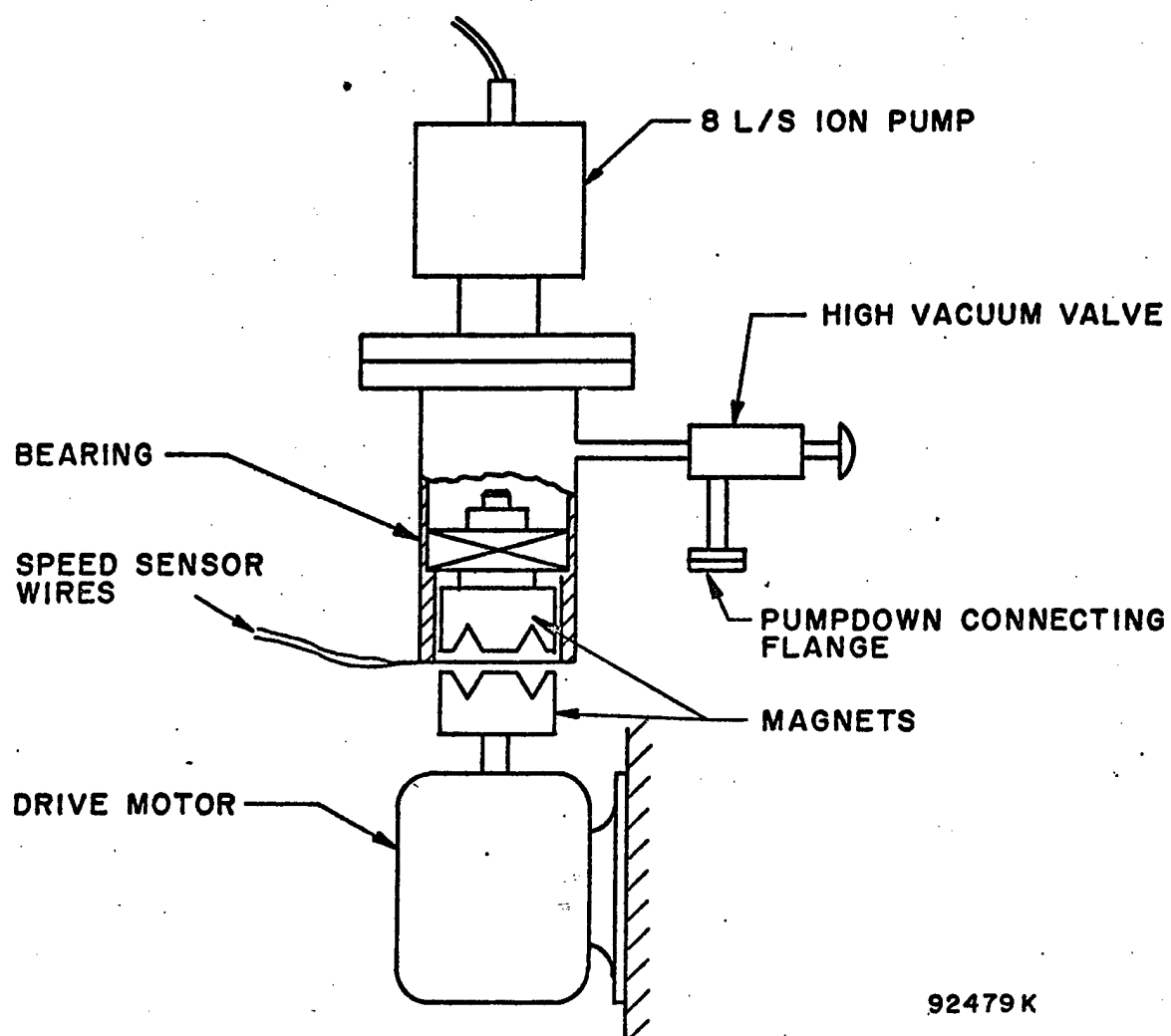
Investigation of the processing parameters with some of these compact materials indicate that considerable improvement in properties can be obtained. Fracture strength can be increased while a reduction in wear by factors of 6 to 10 can be realized. Operating lifetimes of thousands of hours with these type materials create the potential for use in mechanical systems such as that described by Devine et al., in their paper.

#### Summary

There are many solid lubricating materials available from which one may choose. We have attempted to show that not only is the selection of the proper material important but also that the method of application or processing plays an equally important role. Some materials lend themselves only to certain application procedures. New methods of application can increase the potential and usefulness of many of these



materials. Effort must be continued to develop new solid lubricating materials as well as new ways to apply and handle them, in order to obtain the longer operating times required in hardware systems.



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Figure 1. Vacuum Bearing Rig

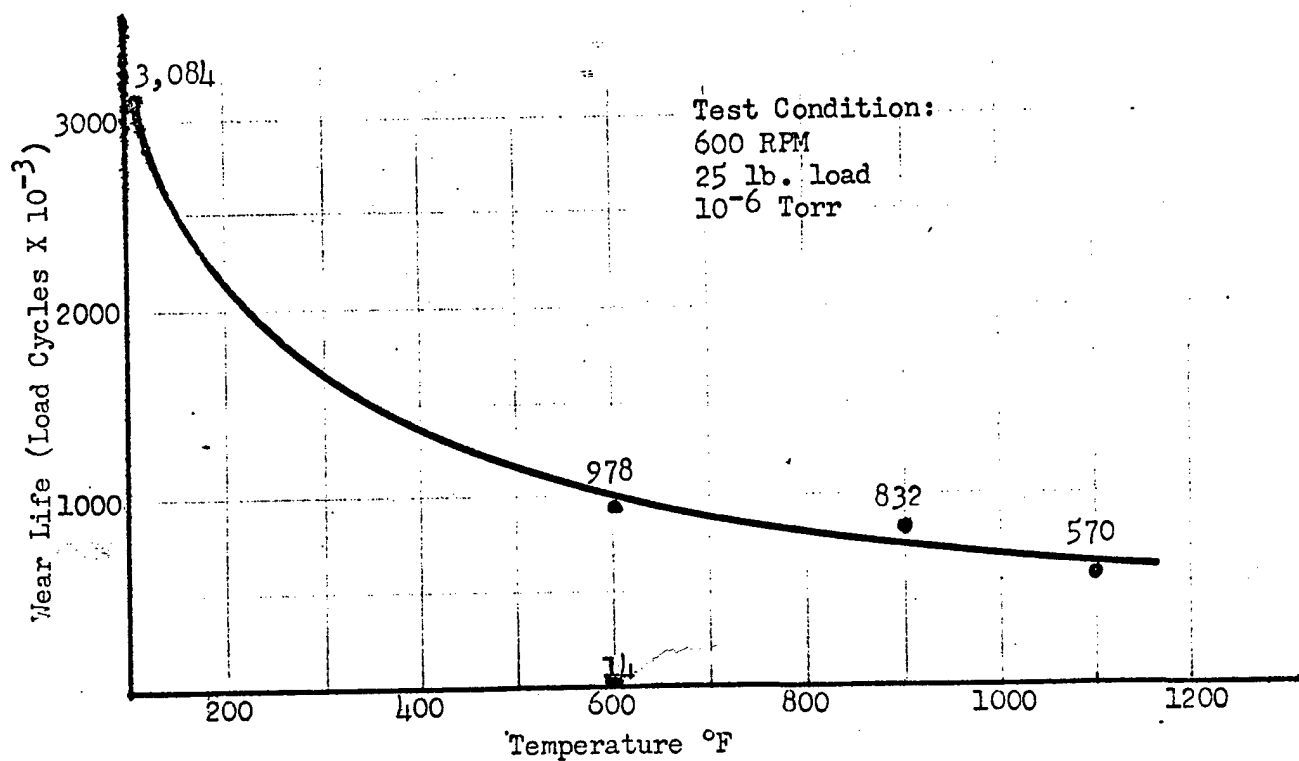


Figure 2. Wear Life Of Double Deposited Film

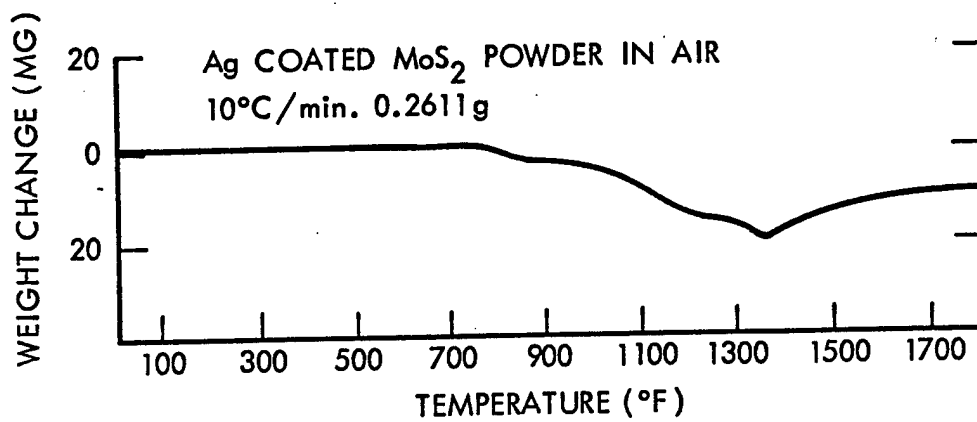
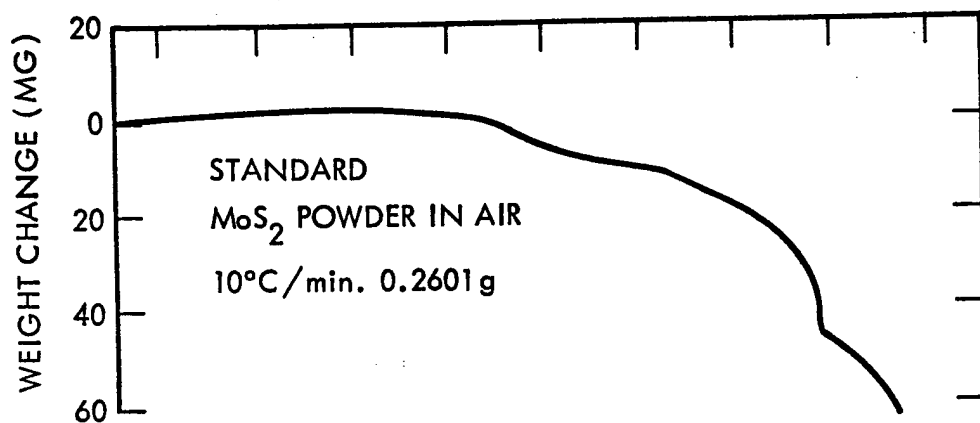


Figure 3. Thermal Stability Of Molybdenum Disulfide Powder  
Versus Silver Coated Molybdenum Disulfide

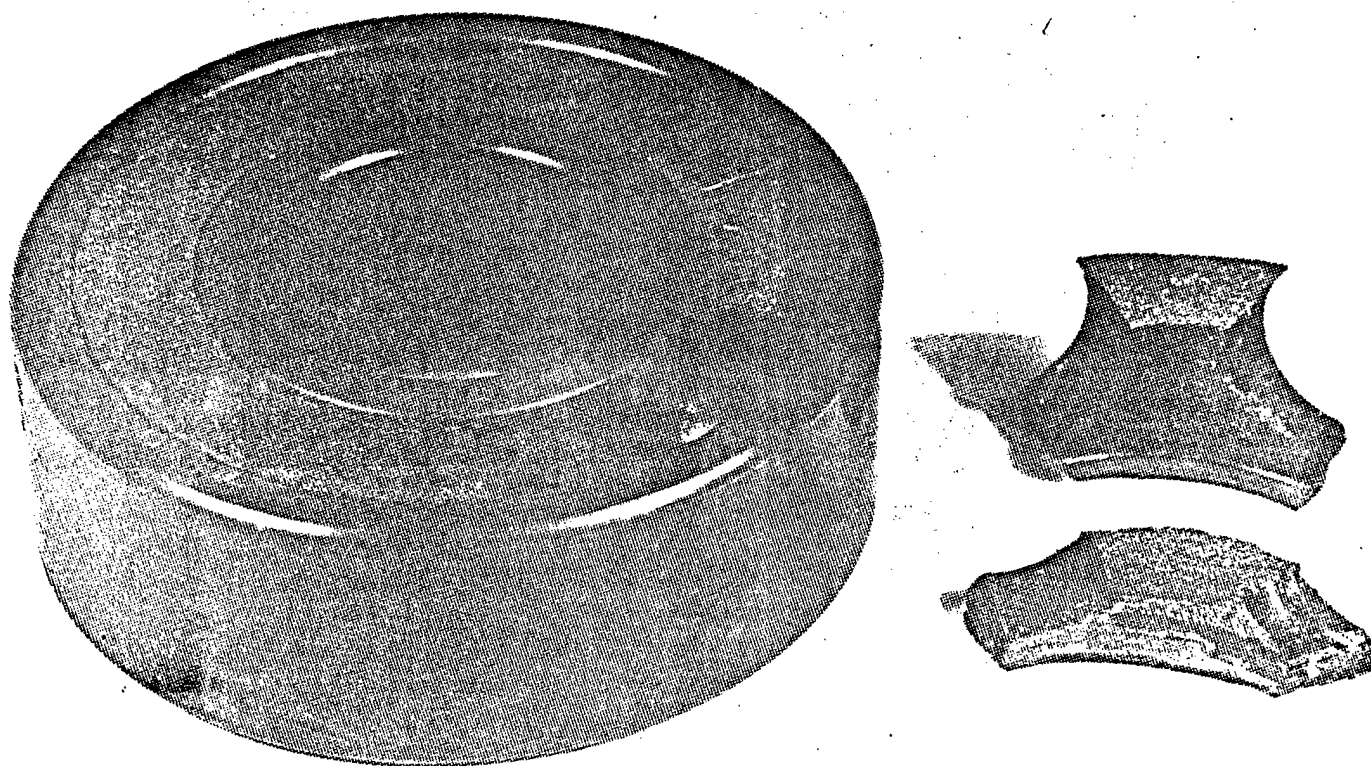


Figure 4. Bearing With Lubricant Compact Separator

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